

# **SERIIUS-MAGEEP Visiting Scholars Program**

## **Final Report**

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**Sandia National Laboratories**

**Project Name:** Coupled optical/thermal/fluid and structural analysis of air and supercritical CO<sub>2</sub> solar receivers

**Project Supervisor(s):** Dr. Vinod Srinivasan and Dr. Pramod Kumar (Indian Institute of Science, Bangalore, India)

**SERIIUS Project #:** CSP-1 High-temperature, pressurized CO<sub>2</sub> receiver



## 1. Introduction and Description of Research Objectives

Recent studies have assessed closed-loop supercritical carbon dioxide (s-CO<sub>2</sub>) Brayton cycles to be a higher energy-density system in comparison to equivalent superheated steam Rankine systems. At turbine inlet conditions of 700°C and 20 MPa, a cycle thermal efficiency of ~50% can be achieved. Achieving these high efficiencies will help concentrating solar power (CSP) technologies to become a competitive alternative to current power generation methods. To incorporate an s-CO<sub>2</sub> Brayton power cycle in a solar power tower system, the development of a solar receiver capable of providing an outlet temperature of 700°C (at 20 MPa) is necessary. To satisfy the temperature requirements of an s-CO<sub>2</sub> Brayton cycle with recuperation and recompression, the s-CO<sub>2</sub> must undergo a temperature rise of ~200°C as it flows through the solar receiver. The main objective is to develop an optical-thermal-fluid and structural model to validate a tubular receiver that will receive a heat input ~0.33 MWth from the heliostat field at the National Solar Thermal Test Facility (NSTTF), Albuquerque, NM, USA.

We also commenced the development of computational models and testing of air receivers being developed by the Indian Institute of Science (IISc) and the Indian Institute of Technology in Bombay (IIT-B). The helical tubular receiver is expected to counteract the effect of thermal expansion while using a cavity to reduce the radiative and convective losses. Initially, this receiver will be tested for a temperature range of 100-300°C under 1 MPa of pressurized air. The helical air receiver will be exposed to 10kWth to achieve a temperature rise of ~200°C. Preliminary tests to validate the modeling will be performed before the design and construction of a larger scale receiver.

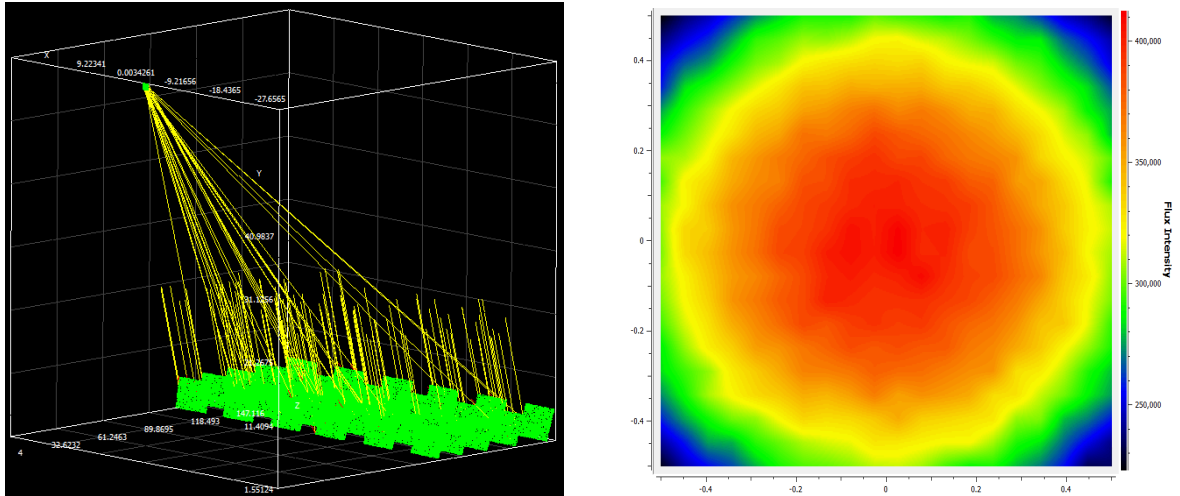
Lastly, I focused on the development of a new computational tool that would allow us to perform a nodal creep-fatigue analysis on the receivers and heat exchangers being developed. This tool was developed using MATLAB and is capable of processing the results obtained from ANSYS Fluent and Structural combined, which was limited when using commercial software. The main advantage of this code is that it can be modified to run in parallel making it more affordable and faster compared to commercial codes available. The code is in the process of validation and is currently being compared to nCode Design Life.

## 2. Methodology

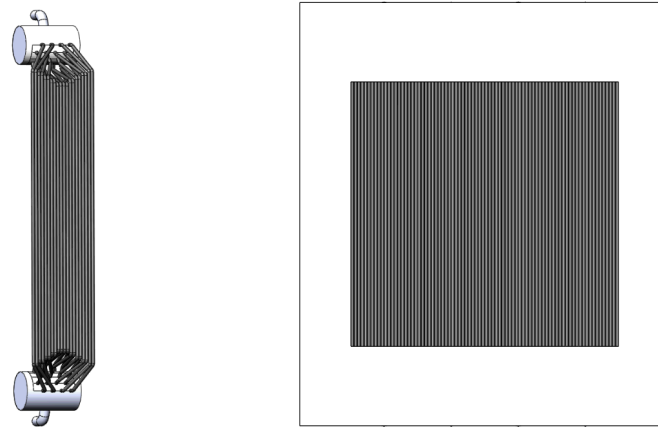
The ray-tracing tool SolTrace was used to obtain the irradiance distribution on the surfaces of the receiver. Since this receiver will be prototyped and tested by the Solar Thermal Technologies group at the National Solar Thermal Test Facility (NSTTF), the heliostat field was used as an input for the irradiance distribution on the receiver (Fig.1). The receiver will have an exposed optical intercept of 1m x 1m which will correspond to 4 panels, of 20 tubes each (Fig. 2), which in turn are 80 - 1/2" tubes. Computational fluid dynamics (CFD) modeling using the Discrete Ordinates (DO) radiation model coupled to the k- $\omega$  Shear Stress Transport (SST) turbulence model were used to predict the temperature distribution and the resulting thermal efficiency of the receiver.

The effect of the tubular arrangement (Fig.3) for enhanced light trapping and reduce thermal emittance was studied. Enhanced aiming strategy or variable flow patterns are other options that will be looked in the future. The receiver surface temperatures were limited to be within the safe operational limit while operating to achieve an outlet temperature of 700°C. The temperature distribution in the tubes will be used to estimate the structural integrity of the tubes and the long-term feasibility of the receiver.

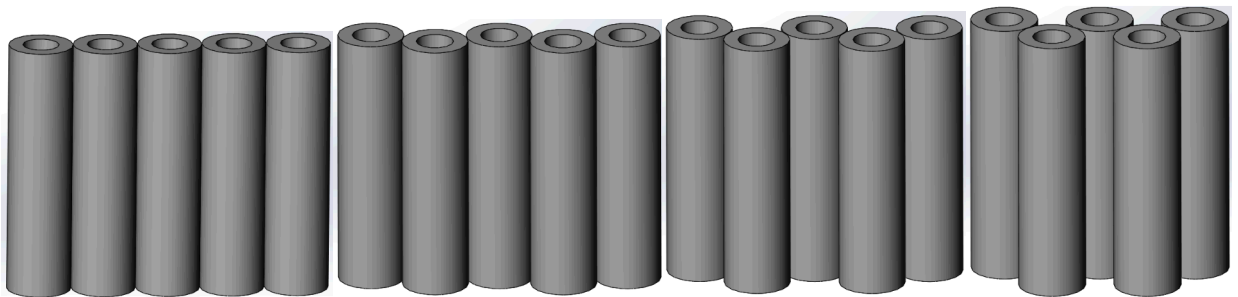
The ultimate goal of this work is to achieve a receiver efficiency of 90% at 700°C fluid outlet temperature, which corresponds to the new design goals targeted by the SunShot Initiative.



**Figure 1. SolTrace ray-tracing analysis on an aperture of 1m x 1m with a single aim-point at the center of the aperture using 30 heliostats at the NSTTF.**



**Figure 2. Left: Single tubular panel with 20 – ½” tubes connected to top and bottom headers. Right: Four panels covered by insulating board allowing a 1m x 1m optical intercept.**

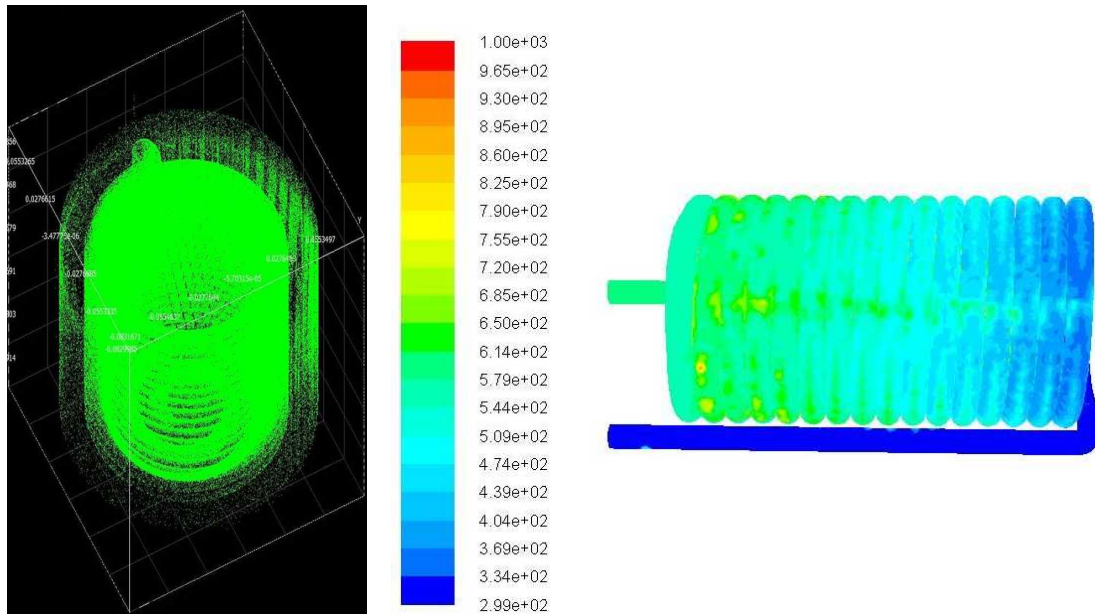


**Figure 3. Tubes with offsets of 0°, 15°, 30°, 45° (L to R) [“U.S. Patent Application 14/743,319, Filed Jun. 18, 2015, Solar Thermal Receivers with Multi-Scale Light Trapping Geometry and Features”].**

The tubular receiver developed by IIT-B (Fig.4) consists of a helical tube inside a cavity which will be used to reduce the radiative and convective losses. The helical tubular receiver is expected to counteract the effect of thermal expansion by expanding axially in a spiral manner. Nonetheless, the structural model need to be completed to assure that the behavior is beneficial. Initially, this receiver will be tested for a temperature range of 100-300oC under 1 MPa of pressurized air. The helical air receiver will be exposed to 10kWth to achieve a temperature rise of ~200°C. Preliminary ray-tracing and CFD analyzes (Fig. 5) were performed to better appreciate the thermal distribution throughout the receiver. The temperature distribution in the tubes will be used to estimate the structural integrity of the tubes and the long-term feasibility of the receiver.



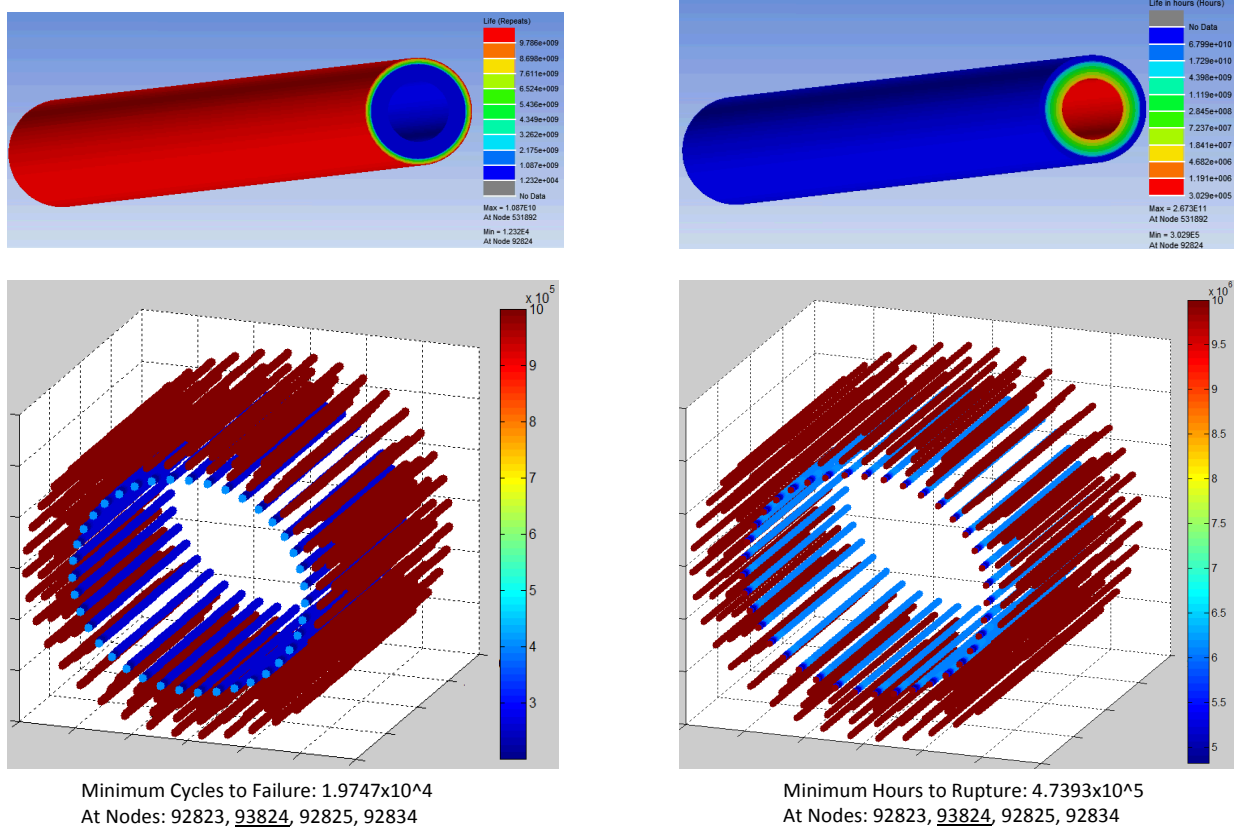
**Figure 4. Helical Tube Air Receiver design by IIT-Bombay which will be tested at IISc.**



**Figure 5. Left: Ray-tracing on the Helical Tube Air Receiver. Right: Temperature distribution on the surface of the receiver.**

Previously, we had been using nCode Design Life to analyze the creep-fatigue damage accumulation on the tubes of the solar receiver. nCode is computational tool the performs these type of analyses using results from ANSYS Structural and ANSYS Thermal (.rst and .rth files). Unfortunately, as we need to couple the thermal-fluid results from ANSYS Fluent, the tool is not able to evaluate the creep-fatigue accumulated damage using the temperature distribution files from Fluent.

The development of a new computational tool that would allow us to perform a nodal creep-fatigue analysis on the receivers and heat exchangers, using the results from Fluent and Structural is required. We have developed a simple tool using MATLAB and is capable of processing the results obtained from ANSYS Fluent and Structural combined. Aside from being able to couple Fluent and Structural results, this code is that it can be modified to run in parallel making it more affordable and faster compared to commercial codes available. The code is in the process of validation and is currently being compared to nCode Design Life.



**Figure 6. Comparison of the new Creep-fatigue analysis tool. Top-Left: Results of number of cycles to failure using nCode. Top-Right: Results of number of hours to rupture using nCode. Bottom-Left: Results of number of cycles to failure using our new code. Bottom-Right: Results of number of hours to rupture using our new code.**

### 3. Presentations and Publications Made or Anticipated in Future

We have identified five possible publications which will reflect the work that Sandia National Laboratories and IISc have performed together. Two journal articles and one conference paper will be led by myself while I will be supporting two more journal publications. We have considered an opportunity to

submit the four journal papers to the SERIUS special issue on the Applied Heat Transfer Journal. The following are the proposed titles and respective supporting authors.

- 1) S. D. Khivsara, R. Bapat, J. D. Ortega, V. Srinivasan, P. Dutta, *Design and Analysis of an Air-supercritical Carbon Dioxide Printed Circuit Heat Exchanger* (Under preparation for Journal)
- 2) J. D. Ortega, S. D. Khivsara, J. M. Christian, J. E. Yellowhair V. Srinivasan, C. K. Ho, P. Dutta, *Coupled Modeling of a Directly Heated Tubular Solar Receiver for Supercritical Carbon Dioxide Brayton Cycle, Optical and Thermal-Fluid Evaluation* (Under preparation for Journal)
- 3) J. D. Ortega, S. D. Khivsara, J. M. Christian, V. Srinivasan, C. K. Ho, P. Dutta, *Coupled Modeling of a Directly Heated Tubular Solar Receiver for Supercritical Carbon Dioxide Brayton Cycle, Structural and Creep-Fatigue Evaluation* (Under preparation for Journal)
- 4) S. Sherma, S. D. Khivsara, J. D. Ortega, S. Singh, *Computational Optical-Thermal-Fluid Modeling of a Helical Direct Tubular Air Receiver* (Under preparation for Journal)
- 5) J. D. Ortega, S. D. Khivsara, J. M. Christian, C. K. Ho, *Creep-fatigue evaluation tool for Solar Receivers and Heat Exchangers* (Under preparation for ASME Conference Proceedings)

#### **4. Next Steps & Future Work**

##### **a) Compare different aiming strategies using the ray-tracing model**

One of the goals of the ray-trace modeling is to achieve the most uniform heat flux distribution on the receiver's surface. We have identified several configurations which we can explore to achieve the heat flux condition. Also, it is important to identify which heliostats from the NSTTF will be used for the prototype testing next summer.

##### **b) Enhanced heat absorption by different flow patterns**

As it has been observed before, flow patterns can benefit or harm the efficiency of a direct receiver. We have identified several flow patterns which could be good or bad for the performance of the receiver. We have generated a test matrix to perform a parametric optimization with the possible flow patterns and aiming strategies.

##### **c) Complete validation of creep-fatigue tool**

One of the most challenging goals is to validate the creep-fatigue model that I have developed during my visit to IISc. This code uses the results obtained from the previous CFD and FEA models and provides an analytical estimate of the cumulative damage by cycling fatigue and creep straining of the receiver.

##### **d) Complete direct receiver structural analyses**

Once we have validated the creep-fatigue tool, we will use the tool to couple the CFD and FEA analyses to assure the structural integrity of the receiver.

##### **e) Complete helical receiver modeling from IIT-Bombay receiver**

Another major task is to help validate the performance of the receiver developed by IIT-Bombay and currently being tested at IISc. We have built several ray-tracing models and CFD models to

analyze the performance of this receiver. We are using the same conditions used in the test and trying to corroborate the outlet temperature and surface temperatures at the chosen points. Aside from the thermodynamic analyses, we must assure that the receiver will withstand the conditions that the IIT-Bombay team wants to achieve.

## 5. Acknowledgements

I would like to thank the management of SERIUS and MAGEEP for providing me this opportunity to undertake research at the Indian institute of Science. I would also like to thank my advisor at Sandia National Laboratories, Dr. Clifford K. Ho

It was a pleasure working with SERIUS members Dr. Pradip Dutta, Dr. Vinod Srinivasan, Dr. Pramod Kumar, Sagar Khivsara and everyone else at the heat transfer laboratory. My visit to India was an enriching and very entertaining experience that provided me with a opportunity to apply my knowledge of design applied in the field of solar thermal technologies.

Aside from the research experience, I felt I received a fabulous cultural experience where I met wonderful people and I learned a lot about the Indian culture.



Dr. Vinod Srinivasan, Dr. Pradip Dutta and Jesus Ortega with the SERIUS CSP Team from IISc.



**Jesus Ortega with the SERIUS CSP Team from IISc.**

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